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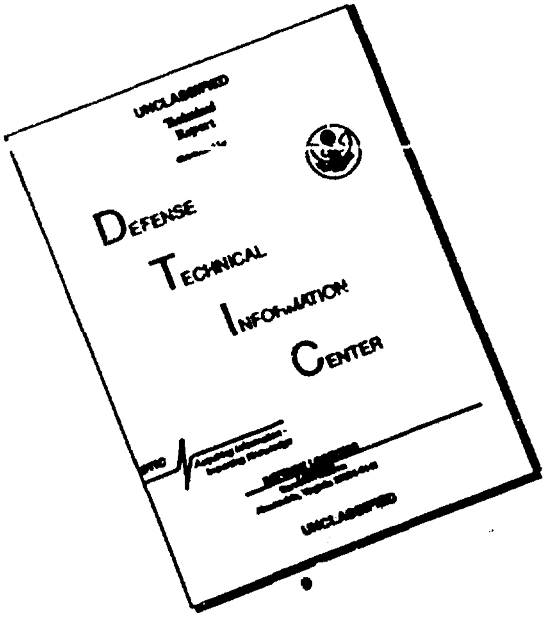


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| 13 ABSTRACT(MAX 200 WORDS) AUSTRALIA'S INVOLVEMENT IN SHOCK TESTING TO EVALUATE THE STRUCTURAL RESPONSE OF NAVAL VESSELS AND SHIPS' EQUIPMENT TO TRANSIENT DYNAMIC LOADS BEGAN IN LATE 1070. IT COMMENCED WITH GAINING THE NECESSARY UNDERSTANDING OF UNDERWATER BLAST PHENOMENA AND CULMINATED IN THE SUCCESSFUL SHOCK TESTING OF AN AUSTRALIAN DESIGNED AND CONSTRUCTED GLASS REINFORCED PLASTIC (GRP) MINEHUNTER. SINCE THEN WE HAVE MAINTAINED AN ACTIVE ROLE IN CONDUCTING FULL SCALE SHOCK TRIALS TO EVALUATE THE VULNERABILITY OF VESSELS AND EQUIPMENT SUPPORTING MINE COUNTER-MEASURE OPERATIONS. WE ALSO CONDUCT SMALLER SCALE TRIALS TO SUPPORT THE SUBMARINE CONSTRUCTION PROGRAM AND THE VARIOUS RESEARCH TASKS UNDERTAKEN BY DSTO. THIS PAPER PRESENTS AN OVER VIEW OF THE SHOCK TRAILS CONDUCTED TO DATE, TOGETHER WITH A BRIEF DESCRIPTION OF FACILITIES AVAILABLE AND CONSIDERATIONS WHICH NEEDED TO BE ADDRESSED WHEN CONDUCTING SUCH TESTS IN SHALLOW WATER. | | |
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# AUSTRALIA'S SHOCK TESTING CAPABILITY

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## SUMMARY

Australia's involvement in shock testing to evaluate the structural response of Naval vessels and ships' equipment to transient dynamic loads began in late 1970. It commenced with gaining the necessary understanding of underwater blast phenomena and culminated in the successful shock testing of an Australian designed and constructed, glass reinforced plastic (GRP), minehunter. Since then we have maintained an active role in conducting full scale shock trials to evaluate the vulnerability of vessels and equipment supporting mine counter-measure operations. We also conduct smaller scale trials to support the submarine construction program and the various research tasks undertaken by DSTO. This paper presents an overview of the shock trials conducted to date, together with a brief description of facilities available and considerations which needed to be addressed when conducting such tests in shallow water.

## 1. INTRODUCTION

Australia is a relative newcomer to the area of shock testing. The Materials Research Laboratory in Melbourne (MRL), part of the Defence Science and Technology Organisation (DSTO), commenced a shock test program late in 1970 as a consequence of an RAN decision to locally design and construct inshore minehunters. These vessels were to form the nucleus of the RAN mine counter-measures force. The role of these vessels, together with auxiliary equipment, was to seek and destroy sea mines in shallow water. Our initial effort, which culminated in a successful sea trial in 1987 to shock test a prototype minehunter, was dedicated to understanding the science of underwater shock phenomena and the response of structures to shock loadings produced by detonating high explosive charges underwater, the logistics required to conduct such experiments and, evaluating the response of high speed instrumentation in shock environments likely to be encountered during the shock test program.

Since the minehunter program, MRL has continued to evolve its shock test capability, not only its application on first-of-class vessels but also to develop small scale tests to trial items of naval ships' equipment and full scale sections. MRL now provides expert scientific advice and technical assistance to the Australian Defence Force and industry involved in Australian ship construction programs.

The acquisition of valid shock data, ie. shock induced motion, magnitude of the loading on the structure and induced stresses and strains in the structure is still the most formidable consideration when conducting shock trials. Considerable effort is still expended on improving the efficiency of data acquisition systems, analysis procedures, methods of calibrating instrumentation and transducers for measuring shock motion, and underwater blast. The emphasis of this paper will be to present an overview of experiments conducted to date, together with a brief description of the facilities we utilise for conducting these tests.

## 2. FACILITIES

MRL have access to three different facilities which provide flexibility in selecting venues for conducting shock tests, enabling us to carry out full and reduced scale experiments.

### 2.1 FULL SCALE TESTING AREA

The RAN minehunter, its auxiliary vessels and equipment are designed to operate in coastal waters and as a consequence all full scale experiments have been conducted in shallow waters typical of their operating environment. These trials took place in the north eastern part of Australia, Queensland, with the actual site being 20 km off the coast of Townsville at a RAAF

bombing range in Halifax Bay. Halifax Bay was chosen for the minehunter program because it provided the shallow water environment, 20 m, necessary for the test; the site has a flat and well characterised seabed and there were no restrictions on the type of ordnance that could be used to generate the shock environment.

### 2.2 SMALL SCALE TEST FACILITES

#### 2.2.1 Flooded Quarry

MRL leases a flooded quarry located approximately an hour's drive from the laboratory. Its depth (20 m) and size (90 m x 90 m) enable full scale sections and/or panels from a vessel to be tested using reduced explosive charges. The vulnerability of items of ships' equipment, ie. pumps, motors, control machinery etc. to specific shock loadings can also be evaluated by mounting them on a purpose designed pontoon. The required dynamic load is achieved by adjusting the distance between the explosive charge and the item being tested. The limitation on the quantity of high explosive that can be detonated is the main disadvantage in using the quarry. This has, for environmental considerations, been restricted to a mass of 25 kg. Despite this, the quarry because of physical dimensions, enables complex experiments to be conducted efficiently and cost effectively without compromising the quality of the shock data obtained.

#### 2. 2. 2 Fragmentation Pit

This is an in-house MRL facility which was designed for ammunition fragmentation studies. Dimensional constraints (2 m x 3 m) preclude its use for most shock test applications due to the complex set of shock waves reflecting from the sides and bottom of the pit. A summation of these waves can result in a test item being subjected not only to much higher loads than initially intended but also multiple loadings. Although extremely limited, the fragmentation pit does provide a convenient facility to function test underwater pressure transducers used to measure the dynamic loads prior to their deployment during full scale or small scale experiments.

## 3. SHOCK TEST EXPERIMENTS

Full scale shock tests were undertaken to support the RAN's mine countermeasures (MCM) operations. The MCM force comprising two purpose designed vessels, two auxiliary mine sweeping craft of opportunity (COOPs) and two remotely operated vessels (drone boats) was tested using the same procedures with minor differences in approach reflecting operational considerations and data requirements. The objective of these tests was to evaluate their shock survivability to dynamic loads likely to be encountered during normal mine sweeping operations. In all tests the data requirements included measurements of shock response throughout the vessels using motion transducers and high speed cine and, the magnitude and duration of shock load using underwater pressure transducers.

The shock environment was generated using explosive filled military weapons which, although not ideal, from an experimental point of view was the most cost effective approach. To simulate mine explosions the charges, either as single items or in clusters, were placed on the seabed and detonated, simultaneously in the case of the grouped munitions. The sizes of the clusters ranged from 1-8 items of ordnance depending on the environment required.

Conducting shock experiments in shallow water with the explosives laid on the seabed presents a number of challenges not normally a major consideration during deep water tests. Both surface cut-off and bottom effects can significantly modify the pressure-time waveform and

hence the resultant load experienced by the target items. It is important that these considerations be taken into account when designing the overall charge/target geometry to ensure that the desired shock loads are achieved particularly when undertaking experiments which need to comply to an agreed specification or standard.

Surface cut-off is a phenomenon related to the leading edge of the shock wave reaching the air-water interface before reaching the target. The resultant rarefaction wave is opposite in phase to the principal shock wave which when they overlap tend to cancel each other out (Figure 1).

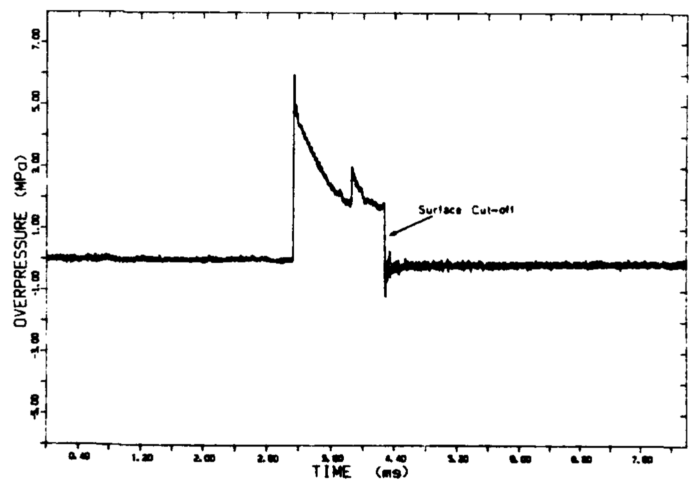


*Figure 1: Pressure-time history exhibiting the influence of surface cut-off*

Bottom effects such as the precursor shock is attributed to the shock wave, from a detonation on the seabed, travelling faster through the seabed which is the more dense medium. Because of the differences in speed a component of the reflected wave can reach the target before the principal wave (Figure 2).

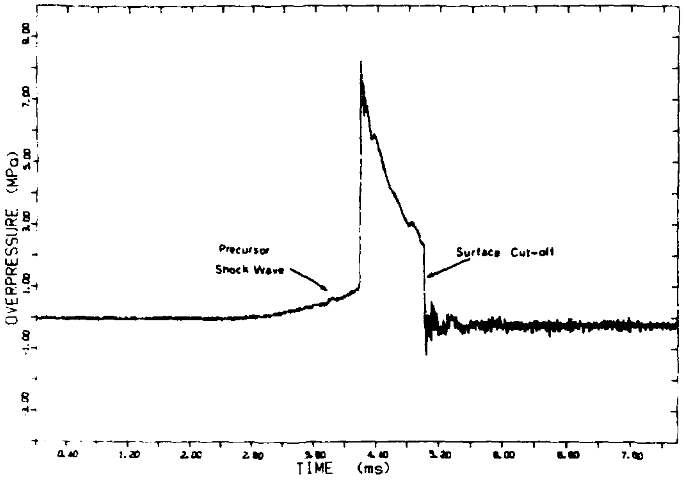


*Figure 2: Pressure-time history exhibiting both precursor shock and surface cut-off*

3.1 HMAS SHOALWATER

HMAS Shoalwater and her sister vessel HMAS Rushcutter are glass reinforced plastic catamarans. They carry out mine countermeasures using remote control techniques allowing the vessels to remain a significant distance from any suspect mines. Shock testing HMAS Shoalwater in 1987 (2) culminated some 10 years' effort to establish a capability for conducting such trials within Australian. The tests were in accordance with NATO standard 4137 which now forms the basis of our current shock testing procedures. The standard requires a first-of-class vessel to be subjected to at least three shock loads up to and including its design level. During the trial, HMAS Shoalwater was moored in a fixed position and subjected to seven detonations two of which were at the design level. Most charges were positioned amidships although a few were positioned forward and aft of this position to induce a whipping effect.

Two different charge sizes were used with the larger charges being comparable to sea mines. To achieve the required shock loads the distance between these charges and the vessel resulted in a slant angle (the angle between the seabed and the straight line joining the charge and the vessel) of about 20 degrees. This is generally regarded as the threshold angle below which surface cut-off and bottom effects can significantly modify the shock load. The smaller charges which were placed closer to the vessels overcame this problem.

The response of the vessel and nominated items of equipment to the different shock intensities was measured using motion transducers (accelerometers, velocity transducers), strain transducers and high speed cine set at 500 frames per second. For each event 22 channels of strain data and 14 channels of motion data (9 acceleration and 5 velocity) were recorded. Additional sites were selected and prepared prior to the trial and were connected to the recording instrumentation when required.

The intensity of the shock loading was measured using four underwater pressure transducers deployed alongside and lowered to a depth of 2 m below the surface. Two transducers were positioned at the centreline with the remaining two approximately 2 m forward and aft of this position to establish an accurate shock profile. To eliminate influences of reflections, the transducers were suspended from telescopic booms 4 m from the side of the vessel. Recording instrumentation was located on 1 Deck (action mess) and secured into three racks fitted with shock mounts for protection against the varying shock environments. The majority of signal cables from transducers located throughout the vessel were fed through a common entry point in the superstructure.

3.2 PERMANENT MAGNETIC SWEEPS (DYADS)

Prior to undertaking seek and destroy operations an array of permanent magnets (Figure 3) are towed through a mine field to activate magnetic sensing mines (Figure 4). The magnets are constructed in two sizes and can be configured to simulate the magnetic signature of a specified class of vessel. They are designed to withstand repeated shock loadings.

*Figure 3: Maxi and Mini permanent magnets*

The purpose of this trial was to assess their structural integrity, linking mechanisms and, to determine whether severe shock loadings would result in degradation of their magnetic field. The charge-magnet geometry for this trial represented a worse case scenario with the charges being detonated directly below the magnets. To achieve the required shock level, multiple charges were used with cluster sizes ranging from one to four items.

This trial was conducted concurrently with a drone boat shock trial (discussed separately in Section 3.4) and resulted in a relatively complicated instrumentation set-up. The pressure transducers were suspended

from the drone boat to a depth of 2 m. The signal was transmitted to recording instrumentation located on a support vessel some 400 m from the transducers.

Ideally the transducers would be placed as close as practicable to the magnets to accurately measure the shock load. However this was not an option because of the likely damage that would be sustained by the transducers. The shock load experienced by the magnets was derived by appropriate scaling of the values measured at the transducer locations. The magnets were subjected to 4 different shock intensities and apart from some minor structural damage, (dishing of the ends) still functioned to their design specification.

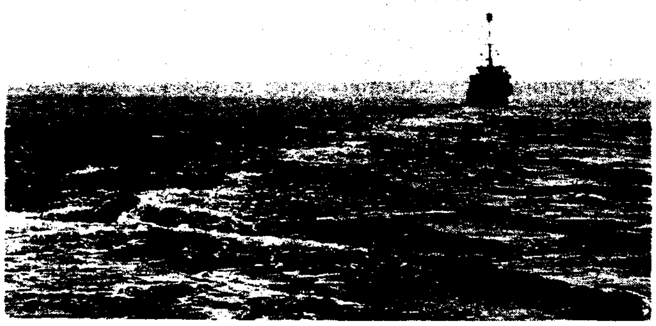

*Figure 4: The magnets being towed behind a Craft of Opportunity: AM Koraaga*

3.3 CRAFT OF OPPORTUNITY (COOP): AM KORAAGA

The COOPs augment the RAN's minesweeping fleet and include fishing trawlers and tugboats. Their role is to tow the permanent magnets (DYADS) through a mine field. The decision to shock test AM Koraaga (Figure 5), a former fishing trawler, was for reasons of opportunity rather than necessity. It was the support vessel for the second drone boat shock trial.

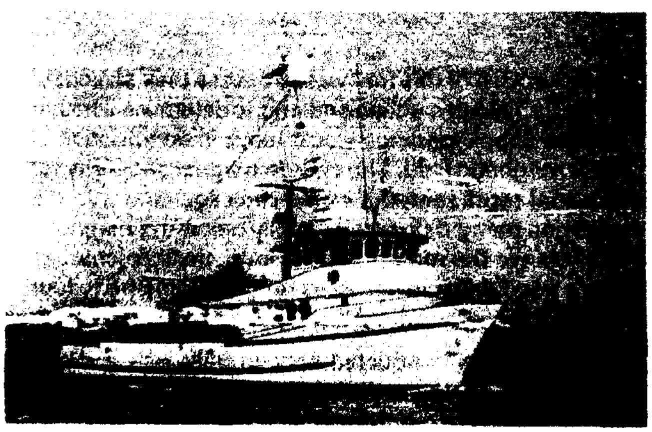

*Figure 5: AM Koraaga*

The results of this exercise were not intended to categorise the vulnerability of the remaining COOPs because of their different designs. The trial did, however, provide an opportunity to obtain information on the resilience of wooden hulled vessels to repeated low shock loads. In normal operations a COOP would be well away from the point of detonation and this was the main consideration when determining the charge geometry which had the COOP moored 150 m from the point of detonation.

The COOP was subjected to three detonations, each of the same intensity, with the position of the detonation being changed for each event, to port, starboard and astern. The shock loading experienced by the COOP was measured in a manner similar to that employed during the minehunter trials. Three pressure transducers were lowered to a depth of 2.5 m, the draft of the COOP, and one to a depth of 15 m to study bottom effects. Again the transducers were deployed about 4 m from the side of the vessel to minimise reflections from the side. During the port and starboard events two transducers were positioned 1.8 m aft of the ship's centreline and the remaining two 3 m forward and aft of this location. For the stern event, two transducers were deployed 1 m either side of the stern centreline. Shock induced motion was measured by deploying 4 accelerometers onboard. The accelerometer locations were approximately in the same vertical plane to measure the deceleration as the shock wave travelled through the vessel. Single accelerometers, orientated vertically, were secured in the bridge and hatchway to the engine room. Two were secured in the engine room in a biaxial configuration, (vertically and transverse).

Pressure and shock motion data were successfully recorded for each event and analysis confirmed that the intended shock intensities were achieved. Post trial analysis revealed that no damage had been sustained by either the hull or ship's equipment. Although the auxiliary minehunting vessels represent a variety of structural designs the trial did establish confidence that the commercial vessels could survive repeated low level shock loadings.

3.4 REMOTE CONTROLLED BOATS

Drone boats MSDX-0 1 and MSDX-02, are remote controlled vessels (Figure 6) used to tow an array of acoustic generators through a minefield to detonate acoustic sensing mines. During normal operations the boats would be between 60-100 m from the point of detonation.

*Figure 6: Shock testing Drone boat, MSDX-02*

The drone boats were commercial fibre glass vessels, with a twin hull form, propelled by outboard motors. The only modification to the design was the inclusion of a fibre glass cover to protect the remote control equipment. The drone boat trials were conducted in two phases and involved two different styles and sizes of vessel. The first phase was conducted jointly with the permanent magnet shock trial (Section 3.2) and involved the first smaller drone boat, MSDX-01.

The aim was to subject the boat to four shock loadings up to a nominated maximum level to assess their structural integrity and the vulnerability of the outboard motor. The maximum load delivered was commensurate with its operational environment and not solely based on design considerations. During operations the boat would be approximately 60 m from a detonation and this together with the explosive mass of a typical sea mine was used to predict the operational shock load. The boat was tested without the remote control instrumentation but was fitted with an outboard motor. It was moored 400 m from a support vessel containing the instrumentation and a short distance from a floating line to which the signal cables leading back to the instrumentation were attached. Four pressure transducers, spaced equidistant along the starboard side of the boat and lowered to a depth of 2 m, measured the shock load produced by the detonations. Four accelerometers in two biaxial configurations, vertical and transverse, measured shock response at single locations on the transom near the outboard motor and in the forward cabin area where the remote equipment was to be installed.

Analysis of the pressure results indicated that the boat was subjected to a slightly lower shock level than intended. Nevertheless the trial was deemed a success as a failure margin had been established. The boat and outboard motor survived the first three shocks however minor damage was sustained after the last high level shock. The leg of the outboard motor collapsed rendering it inoperable. It was not clear from the test whether this was due to cumulative effects of the previous shock environments or solely due to the single high level shock. Just prior to detonation the motor stalled and therefore water, which would have provided some structural support, was not being pumped through the cooling channels and this may be another reason for the damage observed. Damage to the boat itself was restricted to a perforated rubber seal, located on the keel, used to support the speed indicator. Although significant in terms of flooding the vessel a simple design modification would prevent a recurrence of the problem.

Sea trials to evaluate the manoeuvrability of MSDX-01 when operating under remote control highlighted the shortcomings of controlling a single engine boat in moderate to heavy seas, particularly when towing an array of acoustic generators. For this reason a second, twin engine boat, MSDX-02, approximately 8 m in length was commissioned and shock tested. It was initially planned to shock test this boat while it was conducting manoeuvres however this did not eventuate and the exercise was conducted along similar lines as the previous trial. The trial did provide the opportunity to shock test a fully operational boat. Two pressure transducers deployed 2 m below the surface with the data being recorded by a self triggering acquisition system placed onboard. As a back-up against triggering problems, two additional transducers were deployed from the buoys moored alongside and connected via hardwire links to instrumentation onboard a support vessel moored approximately 160 m away.

Six accelerometers in three biaxial configurations, (vertical and transverse), were positioned onboard to record shock motion. Two were located in the forward cabin area to evaluate the effectiveness of shock mounting techniques used to protect the remote control instrumentation and the third on the stem adjacent to the motor closest to the point of detonation.

MSDX-02 was subjected to three detonations the maximum being representative of the shock loadings expected under operational conditions. There was no damage to the hull except from some minor pitting due to fragment impacts and both outboard motors remained operational. Some minor damage occurred to the compass arrangement which controls the boat's heading. If this occurred during an exercise its remote control capability would have been lost, however it could still be driven manually.

## 4. INSTRUMENTATION

Throughout the shock testing program there has been a considerable evolution in the development of acquisition and analysis procedures. Not only have we enhanced our own capabilities but have also supported an Australian equipment manufacturer in the development of a digital recorder designed to operate in severe environments.

### 4.1 UNDERWATER PRESSURE MEASUREMENTS

The pressure-time history of an underwater blast is a fundamental requirement for the analysis of shock phenomena. The data are used to determine the explosive yield of a detonation via the analysis of the first bubble period, the intensity of the shock environment at the measurement point, by integration of the wave form, and the arrival time of the principal shock wave. Pressure transducers, Type PCB 138A with dynamic pressure ranges between 35 Mpa and

70 Mpa have been used for all trials. The transducers were calibrated on-site, before and after the trial, by suspending them from a purpose designed rig and subjecting them to pressure pulses generated by the detonation of 0.5 kg high explosive charges. The charges are accurately made spheres which are centrally initiated using an electric detonator. Both transducers and charges are deployed to a depth of 4 m to eliminate influences due to surface cut-off. Each calibration involves detonating charges at 5 known distances ranging between 2-10 m from the transducers.

## 4.2 MOTION MEASUREMENTS

The shock induced motion was measured using transducers and high speed cine techniques (minehunter trial). Both accelerometers and velocity transducers were used during initial trials primarily to gain a better understanding of their characteristics and to determine which techniques would best suit our future requirements. The reason for utilising accelerometers rather than velocity transducers was that they are readily available, well characterised and their small size made them more manageable. Their disadvantage is that a double integration process is necessary to present the motion data in the accepted displacement-time format.

### 4. 2.1 Acceleration-time

Acceleration-time records were obtained for most trials conducted, the exception being the second drone boat trial. The transducers were configured singly, biaxially or triaxially, depending on the requirements, and where possible positioned in the same vertical or horizontal plane. The data enabled an assessment to be made of the attenuations offered by shock mounting techniques and the transmission of shock through a vessel. The accelerometers, Endevco piezoresistive (Model No. 2264A) were used in conjunction with Endevco signal conditioners (Model No. 4423). They were calibrated before and after the trial. Calibration was performed up to 500 g by dropping a standard accelerometer attached in a "piggy back" fashion to the test accelerometer.

### 4. 2. 2 Velocity-time

Velocity transducers have only been used during phase 3 of the minehunter trial and the first drone boat trial. They duplicated accelerometer positions to obtain comparative data. At this stage their future use will be more as an academic exercise rather than one of direct application. The velocity transducers were manufactured at MRL to the design used by what was then called the Admiralty Research Establishment, Dunfermline, UK. A small number were also provided by them for comparison with the Australian transducers.

### 4. 2. 3 *Strain-time*

Measurement of shock induced strain was recorded during the minehunter trial. These data were used by the ship's designer to identify high stress areas and the effectiveness of different construction techniques. The strain transducers used had an approximate length of 13 mm sufficient to cover 4 webs of the fibre glass material and was deemed sufficient to produce representative strains. Temperature compensation transducers were not used because of the small time duration of the shock induced strain.

### 4. 2. 4 High Speed Photo Instrumentation

High speed photography was a requirement during the minehunter trials to obtain a permanent record of each event and more importantly of any damage that may have occurred. Three cameras, set at 500 frames a second were used, two were placed onboard the target vessel to view equipment of interest and one on the support vessel to provide overall coverage of the event. High speed cine was also taken during the trial testing the permanent magnets, again to provide overall coverage and to assess if any significant movement of the magnets occurred at the time of detonation.

## 4.3 DATA ACQUISTION

Essentially the same acquisition systems were used during each trial. The instrumentation for the minehunter trial was the most comprehensive because of the number of data channels being recorded and the requirement for the remote control of instrumentation such as the high speed cameras and recorders which are required to be switched on and running at their operating speed prior to the charge being detonated. These events, including firing the charge, were controlled in a predetermined order using sequencing instrumentation developed by MRL.

Instrumentation was shock mounted either in a purpose designed rack (minehunter and the first drone boat trial) or in aluminium transit cases fitted with standard 19" racks. The heart of the instrumentation is a 14 channel instrumentation magnetic data recorder, (AMPEX PR 2230 or EMI SE 7000), each have an 80 MHz bandwidth (FM). Although supplemented with digital recording systems the analogue instrumentation is still the most reliable for acquiring data. Digital systems unless fitted with sophisticated triggering mechanisms can still trigger prematurely thereby missing the event entirely.

The digital systems used during the trials enabled selected records to be displayed immediately after the event and analogue taped data to be digitised for preliminary analysis. On-site analysis of pressure-time records using in-house software enabled ready confirmation that predicted shock loadings were achieved. The procurement of faster digital systems with more reliable triggering mechanisms and longer storage capacity will no doubt in the long term reverse the reliance on analogue systems.

## 4.4 Data Reduction

Our data reduction and analysis capability has undergone significant changes since the minehunter trials. At that time we had a limited facility for producing annotated results and analysing the data. Advances in technology and the availability of more powerful computing instrumentation has enabled development of ruggedised field systems, utilising existing instrumentation, to perform analytical functions normally undertaken in the laboratory. This has greatly increased our data processing capability and turn around time in presenting results. Analogue data from the taped recording are digitised through an oscilloscope and transferred to floppy disk via an IBM compatible personal computer. The data are then analysed using a program, called "Blast"[3]. "Blast" was developed because commercial software compatible with the variety of instrumentation currently used is not available. The software analyses the data in terms of voltage-time and applies the appropriate factors for conversion into annotated pressure, acceleration and

strain time histories. Appropriate algorithms are used to further analyse this information to produce the required acceleration, strain data and peak pressure, positive phase duration and shock intensity at the pressure transducer location .

## 5. CONCLUSIONS

The trials were successful both in terms of assessing the integrity of the vessels and fitted equipment and measuring the required parameters. Underwater pressure data have been recorded from a variety of cased munitions and have been analysed to determine resultant shock levels. A large quantity of shock motion data have also been acquired for vessels with different modes of construction . This information provides a significant data base which can be used to, support research and development programs related to underwater shock phenomena, investigate the response of construction materials and naval vessels to different shock loadings and, aid the Australian Defence Forces and industry involved in future ship construction programs.

Using cased munitions to generate shock environments has for most trials been quite successful. Only one anomalous result was obtained during the second drone boat trial. Pressure-time records from one event, which utilised a cluster of eight items of ordnance, showed two distinct pressure peaks separated by a time interval of 0.8 ms indicating that the charges did not detonate simultaneously as intended but as two separate groups. It was for this reason that the predicted shock loading for this event was lower than anticipated.

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